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Heating of Tantalum Plasma for Studies on the Activation of the 6.238 keV Nuclear Level of Ta-181

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1. Introduction

Previous reports[1] have indicated that the activation and decay of the 6.238 keV nuclear level of ^{181}Ta can be enhanced significantly in femtosecond laser heated tantalum plasmas by electron and X-ray excitation. In the current experiment such enhancement has not been observed thus far[2] and a detailed understanding of the plasma conditions is required to understand the results obtained.

Experiments were carried out using 45 fs Ti:sapphire laser pulses focused with a 20 cm lens to intensities of 0.5 - 8 x 10^{16} Wcm^{-2} in a 10 µm spot (1/e intensity diameter), at 45^{o} p-polarized on rotating tantalum targets. The measured prepulse contrast ratio was 6x10^{-5} for a 45 fs pulse 4 ns prior to the main pulse. Target shots were taken at a 50 µm spacing with six revolutions on one target track and a 50 µm spacing between tracks. Measurements were carried out of the ion emission using Langmuir probes (LP), biased at –76V to be in the ion saturation regime, and Rutherford Backscattering from ions collected on a plastic collector foil and of X-ray emission using both CCD and NaI(Tl) pulse height detection systems.

2. Expected Plasma Scaling

At intensities around 10^{16} Wcm^{-2} the interaction of femtosecond pulses with solid surfaces is dominated by resonance absorption[3,4] and the propagation of a nonlinear heat wave at solid denstiy[5,6] into the target. At intensities above ~4×10^{16} W.cm^{-2} it is expected that vacuum heating will become an important mechanism[4,7]. Although absorption was not measured in the present experiment, it can be expected to be on the order of 50% from resonance absorption as measured in other experiments at comparable intensities[8]. Resonance absorption leads to the generation of hot electrons with an expected hot electron temperature of around 9.6 keV at 10^{16} Wcm^{-2} scaling with the 1/3 power of intensity[3] assuming a cold electron temperature of 500 eV. A nonlinear heat wave will propagate into the target to a depth of z_f ~ 19 to 89 nm with a temperature of T_e ~ 246 to 845 eV for absorbed intensities of $0.25 - 4.0\times10^{16}$ Wcm^{-2} respectively for 50 fs pulses assuming an average Z=20 and correcting the heat capacity to include the ionization energy. A rarefaction wave propagating at the ion acoustic velocity leads to cooling to the depth of the heat front on a time scale of 370 to 940 fs respectively for the same intensities. Thus the cooling time of the plasma is approximately 500 fs. The expected equilibrium ionization states can be calculated from either a Thomas Fermi model[9] or a Collisional Radiative (CR) model[10] which are in reasonable agreement. However, the short interaction time does not allow for equilibrium ionization to be achieved and a time dependent calculation based on the CR model[10] considering the uppermost 6 ionization levels leads to predicted ionization in 50fs to 1ps time durations almost two times lower than the equilibrium values at electron densities of $n_e = 10^{23}$ cm^{-3} and T_e ~ 300 eV. Calculations with 10 times enhanced ionization rates to account for autoionization processes[11] only increases the ionization by about 6. Overall, for the expected temperature range of 200 - 400 eV the ionization charge state is expected to be around Z ~ 20.

3. Experimental Results and Discussion

The Langmuir probe signals measured at 13° to target normal are shown in Fig. 1. A small leading peak and a larger following peak are observed with velocities of $1.2 - 1.5\times10^{5}$ m s^{-1} and $4.9 - 2.8\times10^{4}$ m s^{-1} for intensities of $0.45 - 6.6\times10^{16}$ Wcm^{-2} respectively. Assuming

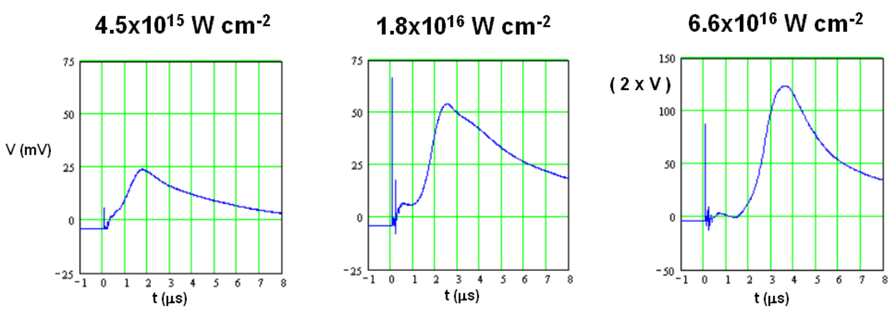


Fig 1. Langmuir probe signals at three different intensities into a 50Ω load. The probe has a 6mm diameter collection surface at a distance of 9.5 cm from the target.

Z = 20 and 10 respectively for the fast and slow peaks, a ratio of specific heats of γ=5/3 and full return of 3-body recombination energy to the expanding plasma the estimated plasma temperatures corresponding[12,13] to these velocities are 213 – 330 eV for the first peak and 66 – 21 eV for the second peak. It is expected that the first peak corresponds to the nonlinear heat wave while the second corresponds to solid target material heated by fast electrons and X-rays. Above $2x10^{16}$ Wcm^{-2} the nonlinear heat wave remains approximately constant while more energy is diverted into hot particles and X-ray emission. The higher particle energies lead to deeper heating of a larger volume resulting in a colder temperature as the intensity is increased. The angularly resolved and integrated Ta flux measured by collection on a Mylar foil with subsequent Rutherford Backscatter analysis using 2.3 MeV He^+ ions is shown in Fig. 2. The integrated flux from the Langmuir probes assuming Z~10 is also shown in Fig. 2. The angular distribution of the Langmuir probe signals was found to fit a $\cos^n(\theta)$ distribution with n ~ 6.3±1. The integrated ion flux from the Langmuir probe is less than the total flux observed on the collector foil as expected since much of the material ablation occurs in the

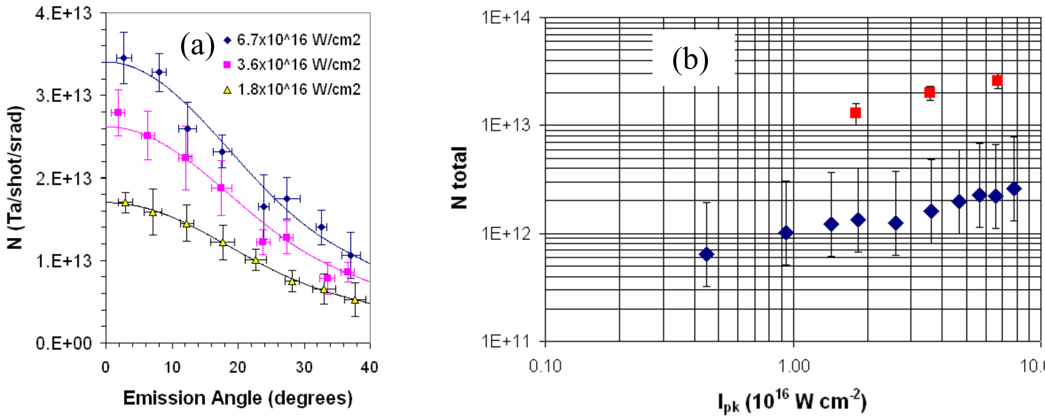
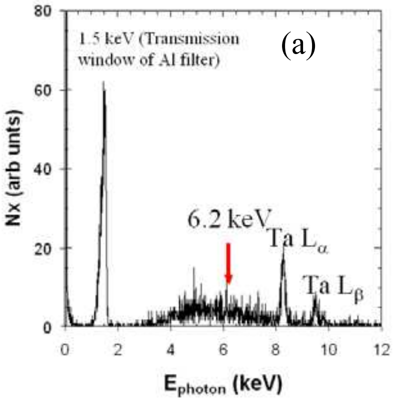


Fig 2. (a) Angular distribution of deposited Ta measured by RBS measurements and (b) total integrated Ta yield from RBS (squares) and from LP measurements (diamonds).

form of neutral particles and shock heated molten material. Measurements of the X-ray spectrum and emission yield at 6.2 keV photon energy using the X-ray CCD camera are shown in Fig. 3. It is seen that the maximum yield at 6.2 keV is equivalent to the emission of a black body at a temperature of ~285 eV for 0.5 ps from a 10 μm diameter spot. Measurements made with the NaI(Tl) detector indicate the appearance of an X-ray tail to several hundred keV for I_{pk} > $2x10^{16}$ Wcm^{-2} corresponding to the generation of superhot electrons. In separate measurements using the Langmuir probe to detect ions from the preplasma alone it was determined that a peak intensity of $2x10^{16}$ Wcm^{-2} is the approximate



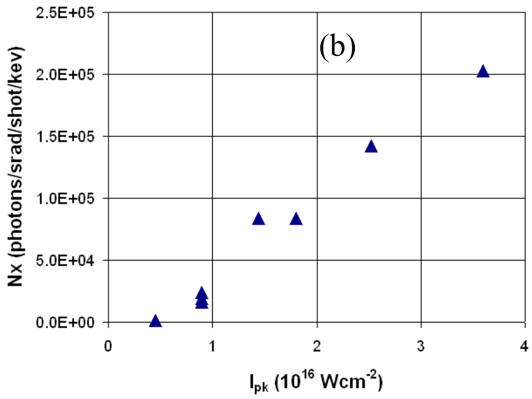


Fig 3. Measurements of X-ray yield at 6.2 keV from X-ray CCD camera: (a) raw pulse height spectrum through an aluminum foil filter and (b) calculated yield of photons at 6.2 keV

threshold for onset of preplasma from the 45 fs prepulse. It is not clear at this point whether the appearance of the super hot electrons is related to the preplasma or to a change in interaction mechanisms such as to vacuum heating.

4. Conclusions

It appears that the short heating time leads to low plasma temperatures and low emission intensities of 6.2 keV radiation which are required for alteration of the nuclear excitation of ^{181}Ta. Formation of a preplasma and changes in the dominant interaction mechanism also effect the results above 2×10^{16} Wcm^{-2} leading to the observation of much more energetic X-ray emission and deeper heating of the bulk target by energetic electrons and X-rays. Further measurements and more detailed modeling are required to clarify these issues.

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